METHODICAL ASPECTS OF INVESTIGATION OF KEROSENE IGNITION AND COMBUSTION IN SCRAMJET MODEL

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Introduction

The latest studies of the overall characteristics of hypersonic flying vehicles with air-breathing engines have shown that these vehicles are fairly promising. Some additional problems arise, however, that are related to the definition of the general shape of the aircraft, the choice of propulsion type and operation regimes, the engine size and position on the aircraft body.

There have been studies on hydrocarbon-fuelled vehicle concept in a range of Mach numbers. It is assumed that the upper bounds of using hydrocarbon fuels lie between Mach numbers 6-8 [1]. Many investigations of scramjets with a hydrogen fuel on models in wind tunnels of are known [2]. But only few works are known, which concerned the study of hydrocarbon fuel combustion and especially combustion of liquid kerosene. Therefore, the investigation of liquid fuel combustion is very important. It is necessary to evaluate the possibility of full engine model tests in a hot-shot wind tunnel under flight conditions.

The main aims of researches were:

- to obtain characteristics of the full engine (and its elements) in ramjet and scramjet regimes;
- to compare these characteristics with the calculation results obtained with CFD and engineering methods;
- to prove the possibility of scramjet tests in a hot-shot wind tunnel;
- to study the ignition and combustion (injection and stabilisation) of a liquid hydrocarbon fuel in scramjet mode;
- to obtain positive effective thrust.

Experimental Facilities

Model. The scheme of engine model and its main elements is shown in Fig. 1. A full engine model consists of three independent modules: inlet, combustion chamber and nozzle. The inlet is a 2-D three-shock system with total turning angle 23.5º. The combustion chamber was an expansion channel with the area ratio of 2.2 and a short length (320mm). Two variants (symmetrical and non-symmetrical) of exit nozzle were studied. Each module can be used in any composition with another elements, and its modification may be realised separately. Besides the possibility to obtain characteristics for each element (inlet, combustion chamber and nozzle) is provided.

The fuel supply system. The fuel supply system is designed to ensure many variants of test conditions, including individual injection of different fuels along the model duct. The fuel system is designed for injection of gaseous and/or liquid fuel to the combustion chamber of the engine and includes two independent systems for fuel supply in the first (in the base region) and

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in the second (from the struts) supply rows. It consists of fuel tanks, fast-response valves, injectors and system for fuel supply and charging (pipelines, joining elements). Each of these two parts is carried out according a two-channel scheme. This construction allows one simultaneous injection of liquid and gaseous fuel into each row of injectors. This should provide better atomisation of the hydrocarbon fuel and better conditions for its self-ignition and combustion. To conduct combustion chamber tests on hydrocarbon liquid fuel, an original fuel tank has been worked out. Pressure measurement in fuel tanks and additional calibration allow one to calculate fuel-air ratio.

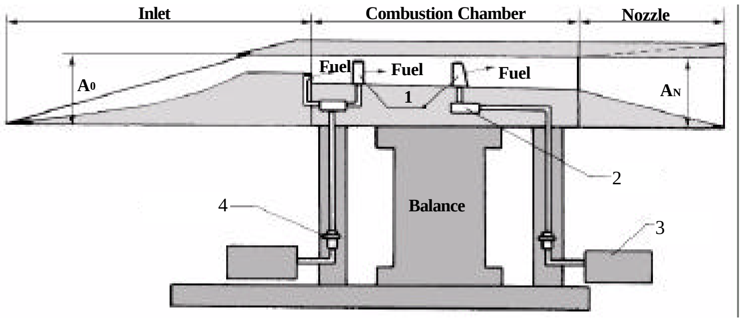

Fig. 1. Scheme of full engine model and systems.
1 – injectors; 2 – force separation system; 3 – fuel tank; 4 – fast acting valve.

The measured parameters include:

- the static pressure distribution along the channel;
- the Pitot pressure field at the inlet exit (the combustor entrance), Pitot pressure field at the exit of the combustor and the nozzle;
- the heat fluxes distribution along the channel;
- the forces acting on the model (three-component balance);
- the fuel flow rate (fuel-air equivalence ratio);
- the combustion efficiency by optical method.

Balance. The three component specialised balance is used for measurement of forces acting on the model in wind tunnels. The major errors of loading determination at corresponding components by the results of initial and control balance calibration were: X<0.15%, Y<0.25%, M_Z<0.25-0.35%. An extra error of the balance by the results of temperature tests: $\delta_{TX1,\,X2} \leq 0.004\%$; $\delta_{TY1,\,Y2} \leq 0.012\%$; $\delta_{TMz1,\,Mz2} \leq 0.008\%$.

For development of a technique of definition of the completeness of fuel combustion (combustion efficiency) the methodical researches on model flames of gaseous fuel were conducted. The method is based on obtaining of calibration relation of integral intensity of luminescence of OH radicals in the ultra-violet range of spectrum (in the band 280…320nm) versus the fuel flow rate under condition of complete combustion. The fuel combustion efficiency for some fuel flow rate is determined by comparison of a value of the ultra-violet radiation intensity of an investigated flame to emission intensity defined on the calibration relation.

Tests were carried out without fuel ("cold" tests) in blow-down wind tunnel T-313 at Mach number from 3 to 6 and without and with fuel ("hot" tests) in hot-shot wind tunnel IT-302M at Mach number 5 and 6. Hot-shot wind tunnel parameters, which were near-flight, are presented in Table 1.

Table 1

M_∞	T_0, K	P_0, bar	P_∞, bar	$Re_1\times10^{-6}$, 1/m
5	1550	46	0.11	12.5
6	1820	100	0.08	15.0

Results and Discussion

The inlet and combustion chamber performances and full engine characteristics without fuel were obtained in a blow-down wind tunnel T-313 [3]. The inlet integral performances are presented in Table 2.

Table 2

M_∞	ν_{th}	f	M_{th}
4	0.46	0.57	1.86
5	0.34	0.73	2.19
6	0.24	0.9	2.44

Visualisation of inlet flow field has shown that inlet start was realised on the model with relative throat height of $0.2A_0$ and $0.15A_0$ at Mach number 4. At Mach number 5 and 6 a relative throat height of $0.15A_0$ was used and inlet was started with high compression level (Fig. 2). At the same time it was determined that designed regime was not realised at Mach number of 6 because of separation of laminar boundary layer on the surface of external compression. Such a flow is typical for tests of inlet models in wind tunnels with low Reynolds numbers. As a result the boundary layer remains as laminar one on the most part of surfaces of external compression and its separation is occurred under an influence of shock waves. It leads to breakdown of flow structure before the channel entrance.

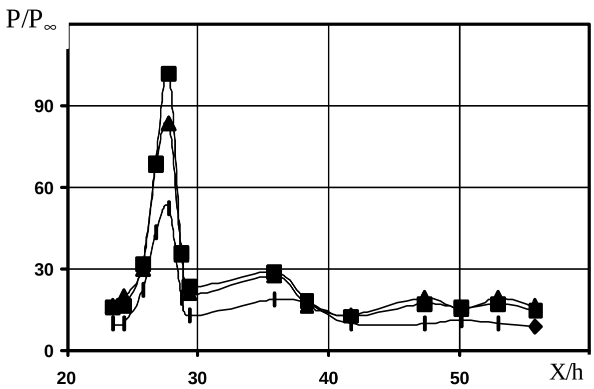

Fig. 2. Static pressure distribution in the inlet throat and combustion chamber.
◆ – M_∞= 5, ■ – M_∞= 6 blow down wind tunnel, ▲ – M_∞= 6 hot-shot wind tunnel.
h – throat height.

"Cold" parameters of the engine in the blow-down wind tunnel and the data in the hot-shot wind tunnel at high temperatures of flow without fuel were compared. The pressure distribution along the model confirm, that in hot-shot wind tunnel a quasi-stabilised flow was established (Fig. 2). This is the base of tests with fuel in hot-shot wind tunnel. The measurement of total pressure distribution at combustion chamber and nozzle exit was carried out in order to find out exit impulse. The example of distribution of the total pressure at Mach number M=6 is given in Fig. 3**.** It can be seen the high level of pressure non-uniformity, which is typical for supersonic flow in the channel at high Mach numbers.

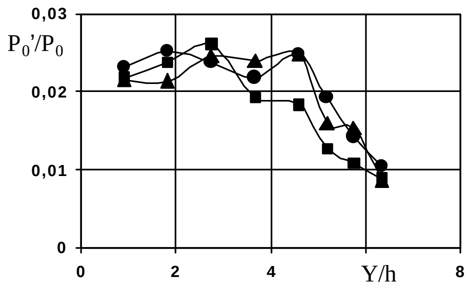

Fig. 3. Relative Pitot pressure at the nozzle exit.
● – Z=-30 mm, ■ – Z=0 mm, ▲ – Z=40 mm.

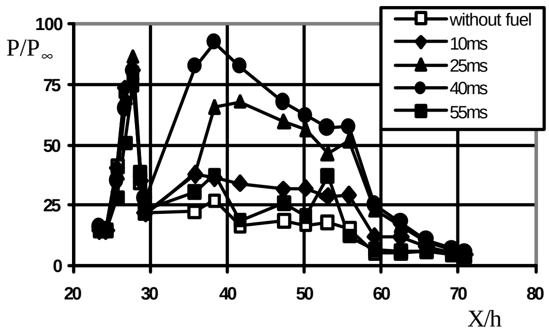

Fig. 4. Relative static pressure along engine channel on bottom surface at M = 6 in hot-shot wind tunnel.

The tests with combustion were realised at the fuel-air equivalence ratio of 0.6~1.2 in hot-shot wind tunnel IT-302M. The operation regime of this wind tunnel is the quasi-stationary. The liquid hydrocarbon combustion leads to significant increase of the static pressure by 4-5 times along the engine channel on the top and on the bottom surfaces (Fig.4). The relative increasing of static pressure due to combustion was approximately the same as for Mach numbers M=5 and 6, but absolute pressure level was essentially different.

The heat flux distribution (Fig. 5) along the combustor is good in accord with static pressure behaviour and also increase more than 4 times. This result corroborates the intense combustion in the engine channel, and a possibility of realisation of combustion process in a relatively short combustion chamber. The calculation of Mach numbers at combustor exit is confirmed that the combustion at a supersonic flow velocity in channel was realised.

The results of measurement of the forces acting on the engine model show that at Mach number M=5 and 6 a positive thrust was obtained. The Fig.6 shows the time change of the engine drag coefficient. The engine drag coefficient remains constant (without combustion) during the whole operation regime of the wind tunnel. The sharp decrease of drag value appears after the combustion process beginning, and the drag level is stabilised after the intensive combustion mode was established. The time change of drag/thrust agrees with the time change of static pressure and heat fluxes along model channel. When the combustion has completed, the drag increased at once to the level of “cold” experiment.

Combustion efficiency was determined by the intensity of ultra-violet radiation of electron-excited radicals of OH. It was found out that at Mach number M=5 the average magnitude of combustion efficiency of the liquid hydrocarbon fuel was close to 0.6. At Mach number 6, the magnitude of combustion efficiency was close to 0.5. Last result demonstrates that additional investigations are necessary to optimise the processes of ignition and combustion for increasing effective engine thrust and for increasing combustion efficiency of fuel.

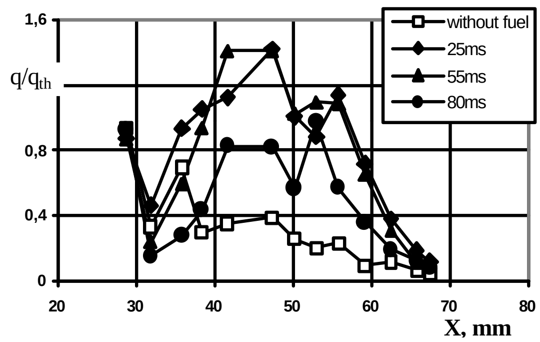

Fig. 5. Relative heat fluxes along engine channel on bottom surface at M=5 in hot-shot wind tunnel.

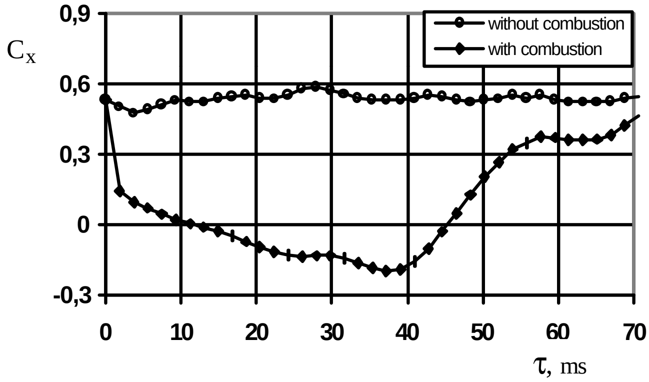

Fig. 6. Full engine drag coefficients with and without combustion at M=6.

Conclusion

The experimental investigations of full model of a hypersonic engine with a supersonic velocity in a combustion chamber allow one to conclude the following:

- high levels of inlet performances were obtained at test in blow-down wind tunnel without adjustment;
- the effective thrust and high level of internal thrust were obtained;
- the possibility was proved of the study of full engine with combustion of liquid hydrocarbon fuel in a hot-shot wind tunnel with operation regime duration of 100…120ms;
- it is necessary to use a pilot hydrogen flame to ignite liquid hydrocarbon fuel;
- the combustion of liquid hydrocarbon fuel at supersonic velocity in combustor was obtained.

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